Angular Distribution of 14-Mev Neutrons Scattered by Protons*

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By bombarding a tritium target with 200-kev deuterons, 14-Mev neutrons were produced. Proton recoils originating in a thin polythene radiator could pass through three proportional counters between which coincidences were observed. By rotating the foil and the counter about the center of the foil the angular distribution of the recoiling protons could be measured. Protons corresponding to neutrons scattered through 90°, 120°, 150°, and 180° in the CM system were observed. Within the statistical accuracy of about 6 percent at each angle the angular distribution of the scattered neutrons appeared isotropic.

INTRODUCTION

An important source of information regarding the nature of the interaction between neutrons and protons is the measurement of the angular distribution of fast neutrons scattered by protons.[1] All recent experiments on neutrons of less than 10-Mev energy are consistent with the assumption of spherically symmetric scattering predicted by most theories.[2] Appreciable deviations from spherical symmetry would be expected on the basis of several of the suggested types of neutron-proton forces for neutrons above 10-Mev energy, and a choice between the various proposed forces would be facilitated by an accurate knowledge of the angular distribution.

Previous measurements[3–5] of the angular distribution of neutrons of energies between 10 and 15 Mev have given results which were not in good agreement. The most recently published results are those of Laughlin and Kruger.[6] These authors observed the scattering of neutrons between 12 and 13 Mev in a cloud chamber and found that the ratio of the differential cross sections for neutron scattering in the backward direction to that for scattering in a direction perpendicular to the incident neutrons was equal to or slightly greater than unity.

The principal difficulty in measuring the scattering of fast neutrons by protons has been that an intense source of monoergic fast neutrons has not been available. The deuterium-tritium reaction, the use of which has recently become possible, furnishes a very convenient source of neutrons for these experiments. It appeared worth while, therefore, to obtain additional data on the angular distribution of the neutron-proton scattering using this source.

APPARATUS

Neutrons were obtained from the reaction

$$T+D\rightarrow He^4+n+17.3 \text{ Mev.} \quad (1)$$

Deuterium ions were accelerated by a Cockcroft-Walton set to an energy of 200 kev. The ion beam was magnetically analyzed, and the monatomic ions were used to bombard a thick target consisting of a zirconium foil in which tritium had been absorbed.[7] The neutrons leaving the target at right angles to the incident deuterons were used in the present experiments; they have an energy of 14 Mev with a spread of about 120 kev. In order to monitor the neutron intensity, α-particles from reaction (1) were counted in a proportional counter. All neutron counting rates will be referred to a fixed number of α-particle counts. Integration of the deuteron current incident on the target could not be used to measure the neutron intensity since the distribution

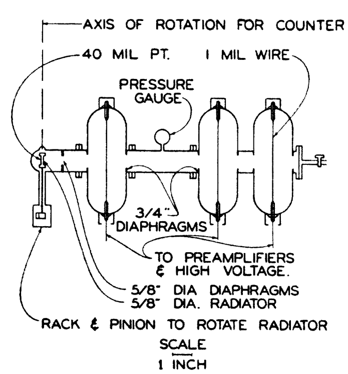

FIG. 1. Triple coincidence counter for detection of recoiling protons.

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[1] W. Pauli, *Meson Theory of Nuclear Forces* (Interscience Publishers, Inc., New York, 1946), p. 55.

[2] A summary and discussion of the experimental results may be found in L. Rosenfeld, *Nuclear Forces* (Interscience Publishers, Inc., New York, 1948), Vol. I, p. 123.

[3] E. Amaldi, D. Bocciarelli, B. Ferretti, and G. C. Trabacchi, Naturwiss. **30**, 582 (1942).

[4] F. C. Champion and C. F. Powell, Proc. Roy. Soc. **A183**, 64 (1944).

[5] C. F. Powell and G. P. S. Occhialini, *Fundamental Particles* (The Physical Society, London, 1947), p. 150.

[6] J. S. Laughlin and P. G. Kruger, Phys. Rev. **73**, 197 (1948).

[7] F. M. Penning and J. H. A. Moubis, Physica **4**, 1190 (1937). Graves, Rodriguez, Goldblatt, and Meyer, private communication.

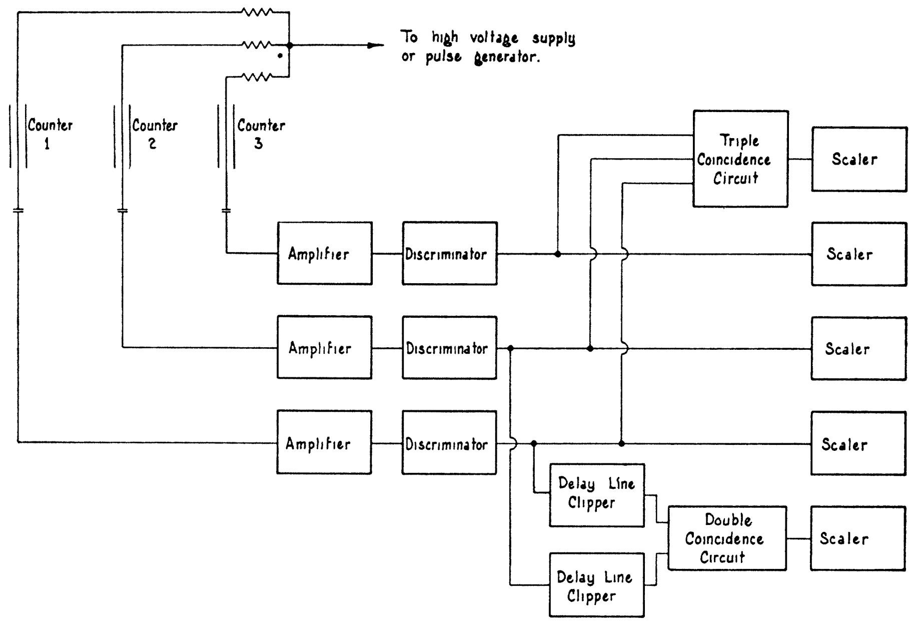

FIG. 2. Block diagram of circuits used to detect protons.

of tritium in the target became quite non-uniform after some bombardment.

The interaction of the neutrons with protons was studied by observing proton recoils originating in a foil of polythene. This foil was located at a distance of 18 cm from the target, it had a thickness of 9.8 mg/cm^2 and a diameter of $\frac{5}{8}$ in., and was backed by a thick layer of platinum. The radiator subtended an angle of 5° at the neutron source.

The recoiling protons were detected in the counter system shown in Fig. 1. They were collimated first by a platinum diaphragm, $\frac{5}{8}''$ in diameter, and then by five apertures, $\frac{3}{4}''$ in diameter, so that only those protons which left the radiator within an angle of approximately 2° from the normal to the radiator could pass through the counting system.

To detect the protons three proportional counters were used, each consisting of a brass cylinder, 4.8 cm in diameter, with a 1-mil tungsten central wire. The counters were filled with a mixture of tank argon and carbon dioxide. Under the conditions of the present experiment a recoiling proton loses less energy in one counter than the maximum recoil energy of a nucleus of the filling gas. Therefore, protons could be identified only by observing coincidences between counters. In addition to the coincidences produced by recoiling protons originating in the radiator, coincidence counts may also be due to accidental coincidences of the many gas recoils, to disintegrations taking place in the walls or the gas of the counter, or to the recoil of light nuclei which might be present in the various parts of the counter. To determine this background the polythene foil could be rotated through 180° so as to expose to the counter the platinum backing, rather than the hydrogenous foil, by the rack and pinion mechanism shown in Fig. 1.

For calibration purposes, each counter was provided with a side tube which contained a plutonium α-particle source. By means of a magnet this source could be moved to the edge of the active volume of the counter or sufficiently far away from it so that the α-particles would not enter the counter.

The electronic circuits used with the counter are shown schematically in Fig. 2. High voltage for the three proportional counters was obtained from a common battery pack. The pulses from each counter were amplified by means of a Los Alamos type 100 amplifier, which has a rise time of 0.5 μsec. and was used with a clipping time of 1.5 μsec. The output of each amplifier was fed into a discriminator which produced square pulses of fixed height. These were counted directly by means of scales-of-64 and recorders, and at the same time they were fed into coincidence circuits. Two circuits were used, a double coincidence circuit which recorded coincidences between the two counters closest to the radiator, and a triple coincidence circuit which detected coincidences between all three counters. In view of the fact that the counting rates recorded from the individual counters were about a thousand times those produced by the protons, a good resolving power was required for the double coincidences. For this purpose the square pulses from the discriminator were clipped by delay lines after 0.5 μsec. The over-all resolving power of the counting system for double coincidences was measured to be 0.8 μsec. by observing accidental coincidences produced by the Pu α-particle sources in the counters. The pulses fed into the triple coincidence circuit were clipped by an RC circuit with a time constant of 1 μsec.; the over-all resolving power of the triple coincidence counting system was measured to be 1.6 μsec. For the proper operation of the coincidence circuits it is essential that the pulses from the amplifier all have approximately the same rise time, since the height of the pulses is not the same in the counters because of the variation of ionization density with range. It was found that if the counters were filled with argon the variation of rise time caused difficulties. When, however, CO_2 was added the drift velocity of the electrons was sufficiently great to make the rise time of the amplifier determine the rise time of the output pulses.

PROCEDURE

To determine the angular distribution of the recoiling protons the whole counter including the radiator could be rotated about an axis in the plane of the foil through its center. In this way the effect of neutrons scattered through different angles could be studied without change in the geometry of the detector. Measurements were carried out for protons recoiling at 0°, 15°, 30°, and 45° with respect to the incident neutrons.

As the counter is rotated the range and ionization density of the recoiling protons change considerably so that the stopping power of the gas and the discriminator biases have to be chosen with some care. The protons emitted in the direction of the incident neutrons have a maximum range of 210 cm in air under normal conditions while the protons recoiling at 45° have a minimum range of 35 cm. If the gas pressure in the counter is chosen such that the protons of shortest range pass through all three counters, the protons of longest range lose only 180 kev in the first counter, which is comparable to the energy lost by β-particles from activities induced by the fast neutrons in the counter walls. Since this makes reliable detection of the protons difficult, two different gas pressures were used in the experiments. Protons recoiling at 0° and 15° were observed with a counter filling of 1.8 atmos. of argon, while for protons recoiling at 45°, 1 atmos. of argon was used. Measurements at 30° were carried out at both pressures.

TABLE I. Experimental results.

Proton scattering angle (lab)	Neutron scattering angle (CM)	Argon pressure (atmos.)		Double coincidences rad. in	Double coincidences	Double coincidences rad. out	Triple coincidences rad. in	Triple coincidences	Triple coincidences rad. out
0°	180°	1.8	Total counts	1059		169	500		25
			Total α's/6400	132		100	132		100
			Lab net		6.33			3.53	
			CM net		1.58			0.882	
15°	150°	1.8	Total counts	607		73	296		15
			Total α's/6400	77		40	77		40
			Lab net		6.05			3.47	
			CM net		1.57			0.899	
30°	120°	1.8	Total counts	984		186	410		21
			Total α's/6400	127		92	127		92
			Lab net		5.75			3.01	
			CM net		1.66			0.868	
30°	120°	1.0	Total counts	690		99	309		13
			Total α's/6400	95		52	95		52
			Lab net		5.34			3.00	
			CM net		1.54			0.866	
45°	90°	1.0	Total counts	1629		351	661		49
			Total α's/6400	249		153	249		153
			Lab net		4.25			2.33	
			CM net		1.50			0.825	

TABLE II. Scattered neutron intensity in center-of-mass system referred to intensity at 180°.

	180°	150°	120°	90°
Double coincidences	1.00 ±5%	1.00 ±7%	1.02 ±4%	0.95 ±5%
Triple coincidences	1.00 ±5%	1.02 ±7%	0.98 ±6%	0.94 ±5%

The discriminator biases were set in the following manner. A generator of artificial pulses was calibrated in terms of energy by comparing the height of the artificial pulses with those from the Pu α-particles. The minimum energy lost by protons in each counter could be calculated. Using the pulse generator, the corresponding bias settings of the discriminators could be determined. The biases were actually set at approximately half this value to make sure that all the pulses due to protons would be counted.

In order to check the setting of the biases, the coincidence counting rate above background was measured at a fixed angle as a function of the bias of each discriminator. It was found that the counting rates were independent of bias over a wide range of biases. The previously described procedure for setting the biases made it possible to select pulses corresponding to the same energy loss even if changes in gas amplification or amplifier gain occurred.

The counting rates observed for double and triple coincidences would be expected to be in the ratio of the solid angles subtended at the radiator by the openings of the second and third counter, respectively. The two methods of counting were used only to afford a check of the proper operation of the counter and of the coincidence counting circuits.

RESULTS

The experimental results are summarized in Table I. For each angle at which observations were carried out, the actual numbers of coincidence counts are recorded, both for experiments with the polythene foil facing the counter and for the background. With each number of coincidences the corresponding number of α-particle monitor counts is given in multiples of 6400. The lines entitled "Lab net" show the coincidence counts divided by the monitor counts minus the corresponding ratio for the background. The following line gives the same number converted to the center of mass system of reference.

For a proton scattering angle of 30° the results obtained at two different pressures are shown. The agreement is as good as can be expected from the number of counts observed. If recoiling protons of lower energy were present, one would obtain a higher number at the lower pressure. Since the observed variation is in the opposite direction, it is unlikely that it is real. For the further evaluation the average of all measurements taken at 30° was used.

In Table II the relative intensity of scattered neutrons in the center-of-mass system is given in terms of the intensity of neutrons scattered through 180°. The error shown with each number is the standard statistical error based on the number of counts observed. The agreement between the results for double and triple coincidences indicates that the counters were working properly. It should be pointed out, however, that the two sets of results are not independent of each other. The largest deviation shown in Table II from the intensity observed for neutrons scattered through 180° is 6 percent which is within the statistical error. Therefore, the results of the present experiments indicate that the scattering of 14-Mev neutrons by protons is isotropic in the center of mass system within 10 percent between scattering angles of 90° and 180°. The resolving power in angle is about $\pm 9°$ in the center of mass system. It was not felt to be worth while to improve the statistical accuracy over that shown in Table II since systematic errors of the order of 5 percent might be present which could not be estimated quantitatively. Such errors might be introduced by the scattering of neutrons in the counter itself, by neutrons scattered by the floor, and by the scattering of recoil protons by the diaphragms and the gas in the counter.

A comparison of the present results with previous investigations is made difficult by the fact that the measurements were carried out at different neutron energies. The measurements of Powell and Occhialini[5] and those of Laughlin and Kruger[6] for neutrons of energy between 12 and 13 Mev agree with the present results within the statistical errors of the three sets of data.

The results of the present experiment refer to neutrons scattered backward. In principle, it should be possible to deduce information concerning the scattering of neutrons into the forward hemisphere by combining the present data with measurements of the total cross section of hydrogen.[8,9] The neutron flux per unit solid angle from the $T^3(d,n)He^4$ reaction at the angle used is known from the alpha-particle count observed simultaneously, under the reasonable assumption that the angular distribution in the center of mass system is spherically symmetric. From this neutron flux and counting rate, the known number of hydrogen atoms in the polythene foil, and the geometry, the differential cross section for 0° in the laboratory system was found to be 0.20×10^{-24} cm^2 per unit solid angle after an 18 percent correction for flux asymmetry was applied. This asymmetry in neutron intensity around the target was mapped with threshold detectors and could be rather well accounted for by inelastic scattering alone. Other experience in this laboratory has shown that 14-Mev neutrons are nearly always degraded in a single inelastic scattering process to an energy at which the coincidence counter could not detect them. The direction of the counter coincided with material of such an amount that 14 percent of the 18 percent could be accounted for by the known inelastic cross sections of the materials, the remainder probably arising from good geometry elastic scattering. The neutron flux was presumed correctly measured by the threshold detectors in a direction where only a $\frac{1}{16}$-in. brass wall lies between source and detector.

The above cross section gives 0.050 barn per unit solid angle for the 0° center of mass value and, if spherical symmetry is assumed, a total cross section of 0.62×10^{-24} cm^2. This latter value is to be compared with an observed value[8,9] of 0.69 $\times10^{-24}$ cm^2. Within the rather large experimental errors of both measurements the agreement is good.

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[8] E. O. Salant and N. F. Ramsey, Phys. Rev. **57**, 1075 (1940).
[9] M. Ageno, E. Amaldi, D. Bocciarelli, and G. C. Trabacchi, Phys. Rev. **71**, 20 (1947).